The geological setting and origin of emerald deposits at Menzies, Western Australia.

by J. D. Garstone

Woodside Petroleum Development Pty. Ltd., 77 St. George's Terrace, Perth, W.A. 6000

Abstract

Emerald has been found associated with a series of north-west trending irregularly shaped pegmatite veins which are concordantly emplaced along schistosity planes within ultramafic rock at Riverina station, near Menzies, Western Australia. The country rock schists have apparently been formed by potassium metasomatism of the ultramafic rock during intrusion of the pegmatite. On average they contain 0.15% Cr_2O_3 and vary mineralogically from predominantly phlogopite schist to rocks that additionally contain hornblende, actinolite, chlorite and talc. Three reaction zones are developed around the pegmatite: (1) hornblende zone, (2) zone of platy phlogopite, and (3) actinolite zone. Beryl is found in the pegmatite, but is more abundant in the surrounding mica schist. Berryllium-bearing solutions have apparently permeated the ultramafic country rock to a maximum distance of 30 cm and extracted small quantities of chromium. Three stages of beryl crystallisation have been recognised. Colourless and pale green beryls formed first, followed by crystallisation of dark green beryl, coloured by chromium; high alkali, chromium-deficient crystals formed last. Emerald, containing 0.15-0.23% Cr_2O_3, probably formed in phlogopite schist during the intermediate stage.

Introduction

Emerald, with diamond, ruby and sapphire is one of the most sought-after and highly valued precious stones. Consequently, the discovery of emerald at Riverina, west of Menzies, Western Australia, could be of economic significance, and has provided part of the incentive for this study.

Emerald is the gem variety of beryl characterised by its rich green colour due mainly to traces of chromium impurity. Anderson (1966) believes that to be classified as emerald, beryl should be coloured by sufficient chromium to show a clear absorption spectrum with the hand spectroscope. It has recently been recognised that vanadium may produce a similar green hue (Taylor 1967). The question of whether emerald-green beryl containing vanadium is classed as emerald arises when appreciable amounts of this element are present.

Emerald finds have been recorded at several localities in Western Australia. The earliest and most productive deposit is at Poona, in the Murchison Division, where emeralds are found in mica schist and pegmatite. Other minor discoveries have been reported from Wodgina, Warda Warra and Melville. Glover (1968) summarises the literature on these deposits and lists sample material held in public institutions in Perth. Emeralds from these sources are apparently associated with pegmatites and schists, as are most of the world's emeralds, with the notable exception of the Columbian gems.

Very little detailed geological research has been carried out on the genesis of such deposits. It is widely accepted that beryllium is introduced by pegmatites, and that chromium is derived from surrounding ultramafic rocks. The emerald deposit at Riverina is here used to examine this traditional model from a geological standpoint. Emerald is treated as part of the sequence of beryl, which is fairly abundant at Riverina. The geology and geochemistry of the deposit have been outlined by a combination of field mapping and laboratory-based studies. Other aspects examined include: geochemistry and mineralogy of the rocks at the emerald deposit, geochemical trends as potential prospecting guides, crystallisation history of the beryl sequence and origin of coloration of beryl.

Menzies is in the North Coolgardie Goldfield, 121°00′E, 29°40′S, at an altitude of 430 m above sea-level, and is connected with Perth by 725 km of sealed roads via Kalgoorlie. The area under review, where emerald and green beryl were discovered in 1974, lies in a greenstone belt some 46 km west of Menzies, on Riverina station (Fig. 1). Low hills and ridges surrounded by alluvial plains define the north-west trending belt. This is a semi-desert region where annual rainfall is variable, but generally low, and vegetation consists mainly of stunted acacias and mixed scrub.

The Menzies area is underlain by Precambrian rocks (see Fig. 1). Kriewaldt (1970) describes the succession as follows:
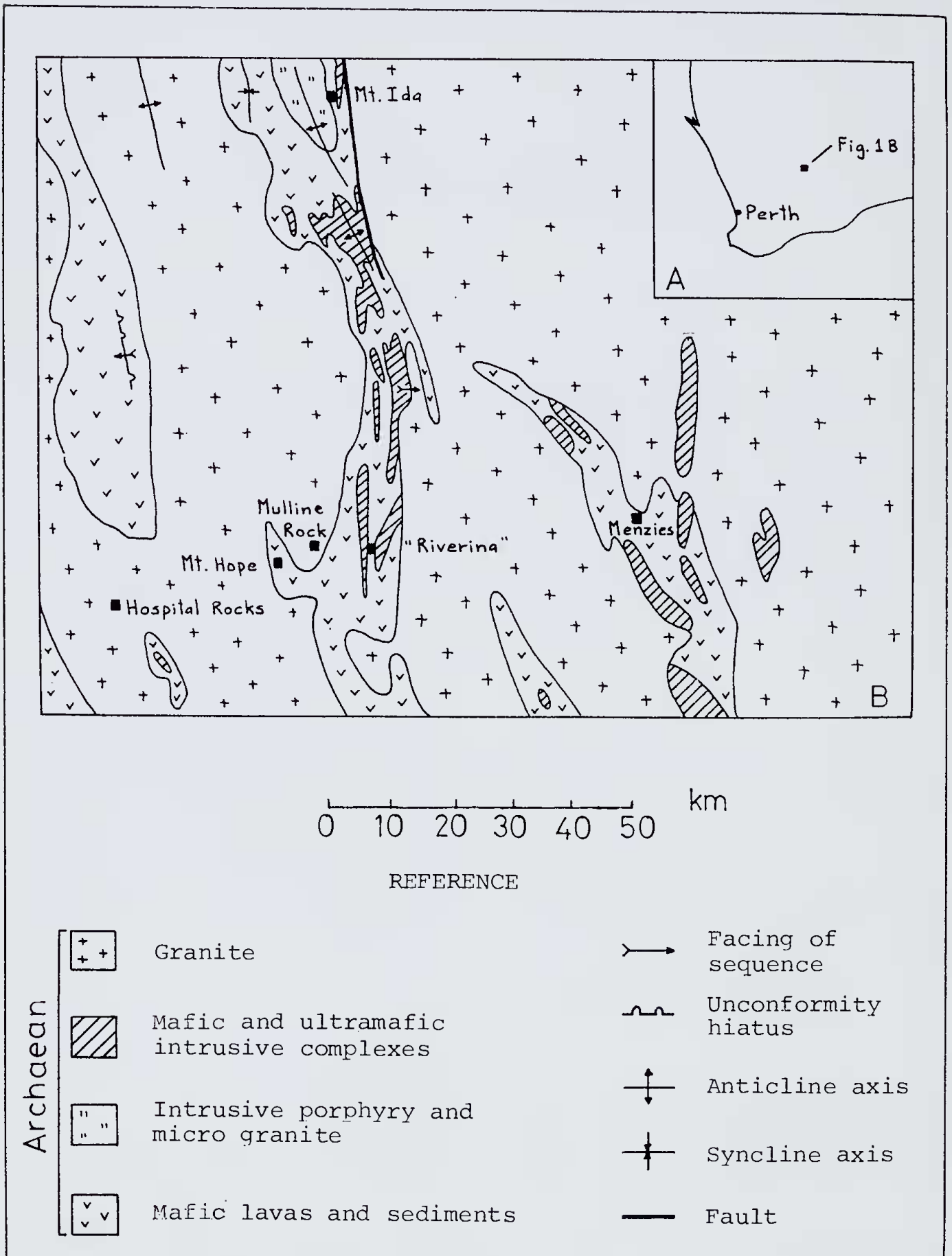
Figure 1.—A. Location map. B. Regional geology of Menzies Sheet SH/51-5 (based on Kriewald 1967).

5. Pegmatite, felsite.

4. Intrusive, granite.

3. Quartz porphyry, ultramafics, and abundant mafic sills which intrude (1) and (2).

2. Talc-chlorite schist, pyritic chert, conglomerate with chert cobbles, basalt, slate, siltstones, grits and acid volcanics.

1. Basalt, quartz-mica schist, slate, greywacke, and banded iron-formation; all intruded by ultramafics.

The layered sedimentary and volcanic rocks are metamorphosed and intruded by a medium-grained biotite granite which is probably about 2 600 m.y. old (Kriewaldt 1970).

Geology of the deposit.

The emerald deposit on Riverina station lies in a greenstone belt that forms part of the Western Australian Archaean Shield. Outcrop is poor and exposure is limited to a sizeable open-cut and several shallow exploration costeans. The geological setting comprises a fairly simple sequence of altered volcanic and ultramafic rocks, intruded by acid veins and dykes (Fig. 2). Beryl and emerald mineralisation are associated with a series of narrow pegmatite veins which intrude the ultramafic rocks. The pegmatite zones will be discussed separately.

Mafic metavolcanic rock

A metamorphosed mafic volcanic unit dominates outcrop in the area and forms low ridges along its contacts with the ultramafics. It is traversed by numerous small randomly-oriented quartz veins. The schistosity of this dark grey, fine-grained unit has a northerly strike. The mafic rock is composed of chlorite, green amphibole and plagioclase, and is clearly metamorphic and of probable volcanic origin. Although usually schistose, microstructures observed in thin-sections of several samples appear to preserve an original texture which has survived amphibolite-facies metamorphism. Typically, small anhedral grains of plagioclase are randomly dispersed throughout the chlorite-amphibole schist; samples showing microstructures contain small, flattened pods of plagioclase enclosed in the matrix schist. These pods may be relict amygdales of an original basalt, or the relict texture of a volcanic agglomerate.

Ultramafic rock

The ultramafic body, approximately 120 m wide, is bounded to the east and west by the mafic metavolcanics already discussed. Relative to the low north-south ridges formed at these contacts, its surface expression is a narrow flat crossed by several small intermittent creeks. Superficial deposits resulting from *in situ* weathering of the ultramafic body mask the underlying rocks. Quartz and acid intrusives crop out but only surface rubble indicates the presence of the ultramafic unit. Relict spinifex texture preserved in a large block of ultramafic rock exposed in the open-cut indicates that it is an ultramafic komatiitic lava flow. A small bed of intercalated ferruginous sediments has been intersected in a shallow costean.

The ultramafic body has been metamorphosed to schist of variable mineralogy. Chlorite schist close to the surface accounts for the dark green appearance of the ultramafic rubble. It probably represents a retrograde phase of metamorphism and results from the hydration and alteration of higher grade ultramafic rock. At the open-cut, where the rocks are exposed to a depth of 7 m below the surface, the ultramafic schist is interfoliated with the mica schist developed at the margins of pegmatite veins. It consists of a crenulated tremolite/actinolite-phlogopite/biotite assemblage. Bladed spinifex texture is preserved by grains of phlogopite cross-cutting a lineated tremolite/actinolite groundmass.

Near-surface material stripped from the site of the open-cut also contains pale-green talcose schist, and chloritic rock traversed by small veins of carbonate and fibrous white asbestos. Talc schist is exposed at depth in the face of the pit and is probably related to the suite of altered rocks bordering the pegmatite. The carbonate and asbestos veins are secondary and restricted to the weathering zone.

Whole-rock analyses of two typical samples of actinolite-phlogopite schist (DUB 1 and 2) show a composition intermediate between basaltic komatiite and peridotitic komatiite. Their chromium content is quite high (0.18-0.31% Cr_2O_3), and the amount of silica they contain places them on the border between basic and ultrabasic rock (See Table 2).

Acid intrusives

A number of acid veins and dykes intrude the volcanic sequence, particularly the ultramafic body, and may be classed as: quartz vein, quartz-feldspar porphyry and granitic vein. These intrusives generally strike east-west; only small quartz veins follow the north-eastward trend of the pegmatite. Field observations and chemical analyses indicate that they are not related to the beryl mineralisation.

The pegmatite

The pegmatite comprises a series of north-east trending veins concordantly emplaced along schistosity planes within the ultramafic body. Some veins are almost wholly composed of feldspar, whereas others contain only blocky quartz or quartz-feldspar intergrowths. They do not resemble the typical pegmatites of granitoid terrains. A striking feature of these veins is the development of phlogopite schist along their margins. Beryl occurs in the pegmatite, but the darker green and emerald varieties, in particular are more abundant in the schist.

The pegmatite is a classic example of what Beus (1962) refers to as a "granitic pegmatite of the crossing-line". Characterised by specific mineralogic-geochemical peculiarities, crossing-line pegmatite fields usually lie in the exo-contact zones of pegmatite-bearing granitic intrusions in metamorphosed mafic and ultramafic rocks. These veins are complex and it is difficult to ascertain whether they are indeed pegmatitic, or more closely related to hydrothermal and pneumatolytic processes.
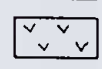
REFERENCE

Quartz vein

Pegmatite and quartz-feldspar porphyry

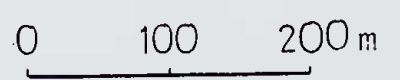Ultramafic rock

Mafic-metavolcanic

em Emerald

Lithological boundary

Inferred boundary

Exploration trench

0   100   200 m

Structure

The pegmatite veins are generally narrow and very irregularly distributed. Their presence is marked by platy black phlogopite schist. Auger drilling to a depth of 1.2-3.0 m aids geological mapping and is particularly valuable in tracing the mica schist-pegmatite zone. Narrow discontinuous fingers of schist have a general north-east trend; the widest developments are at the site of the open-cut and at the intersection with the road.

The structure of the pegmatite is complex and consists of narrow veins up to 0.5 m wide that unite and diverge. Small discrete lenses of feldspar (1-5 cm in length) in phlogopite schist are normally found less than 10 cm from quartz and quartz-feldspar veins. In places, large feldspar lenses are clustered into 'podiform' veins.

Reaction zones

The intrusion of pegmatite veins has resulted in contact metamorphism and metasomatic alteration of the ultramafic host rocks. Zonal structure is characteristic of veins in which feldspar predominates, but not of podiform feldspar and quartz-rich veins. It is evident that volatiles and chemically active fluids which permeated the country rock are closely related to the feldspathic fraction of the pegmatite. In a contact reaction zone such as this, where a concentration gradient is established, mica and amphibole tend to nucleate more easily than other minerals. Three major reaction zones have been formed:

(1) *Hornblende zone*. Acicular blades, frequently altered to bright green clay, penetrate the phlogopite schist bordering feldspar veins. In some hand specimens these blades account for about 40% of the rock, whereas in others they are sparse. The green clay was identified by X-ray diffraction as saponite—a magnesium member of the montmorillonite group, commonly associated with mineral veins (Deer *et al.* 1966). The green blades of clay are the final alteration product of a green hornblende which probably has an unusual composition. Some crystals are weakly zoned. The hornblende forms euhedral crystals, most of which have undergone varying degrees of alteration. The most common alteration product is chlorite and a mineral identified as possibly stilpnomelane.

Hornblende has thus undergone several stages of alteration. Textural evidence suggests that the order of alteration is probably as follows:

hornblende → stilpnomelane → chlorite → saponite.

Preservation of the bladed morphology of the parent hornblende, even when completely broken down to saponite, indicates hydrothermal alteration, probably from pegmatitic waters recirculating during crystallisation.

(2) *Zone of platy phlogopite*. This is the widest reaction zone and encompasses the hornblende zone. Along podiform feldspar veins and quartz-rich veins the hornblende zone is absent, in which case the platy phlogopite zone is developed at vein margins. Clusters and single crystals of beryl, especially emerald, are found in fine lamellar phlogopite.

Phlogophite schist enclosing feldspar pods is intensely folded and deformed. Veins, about 0.2 m wide, of strongly interlocked phlogopite are less common. They have a recrystallised appearance and generally mark the border between phlogopite schist and large bodies of actinolite-bearing ultramafic schist. Minor yellowish green beryl is present.

(3) *Actinolite zone*. The actinolite zone is irregularly shaped and developed intermittently as separate elongate lenses and bands, ranging from a fraction of a centimetre to several centimetres in width. The rock is almost entirely composed of actinolite and phlogopite and is interfoliated with platy phlogopite schist at the intersection of the two zones.

Although the hornblende and phlogopite zones are intimately related to the pegmatite, the actinolite zone apparently represents remnants of the original ultramafic country rock which have been only moderately altered. The medium-grained actinolite rock is schistose and in places severely deformed by microfolding. Crenulation cleavage is developed in some rocks.

Microfolds are present in thin-sections of specimens UB3* and DUB2. Structures and textures in these thin-sections have important implications regarding the paragenesis of the phlogopite. Phlogopite tends to be concentrated along fold axes. A number of phlogopite grains seem undisturbed by the fold axis, whereas actinolite grains aligned along schistosity planes are fractured. It can be inferred that phlogopite formed during the deformation that is assumed to have been coincident with intrusion of the pegmatite. Hence, the phlogopite metasomatism is almost certainly related to emplacement of the pegmatite. Actinolite schist lies farthest from the pegmatite veins and represents the outer limit to which potassium, necessary for the formation of phlogopite, permeated the ultramafic. In the hornblende and platy phlogopite zones the rocks contain mainly phlogopite. Datta (1966) suggests that potassium may form phlogopite by reaction with the Mg-silicates of an ultramafic rock.

Talc and chlorite schist are also found in the sequence of altered rocks surrounding the pegmatite. Beus (1962) includes chlorite and talc zones as part of the reaction complex characteristic of beryl-bearing veins of crossing-line pegmatites, together with the phlogopite and actinolite zones discussed previously. At Riverina the talc and chlorite rocks are randomly distributed and cannot be assigned to specific zones. They lie farthest from the pegmatite veins, beyond the actinolite zone, and result from alteration and hydration of the ultramafic country rock.

Geochemistry and mineralogy

The face of the open-cut is the largest exposure of the pegmatite (38 m long, 7 m deep) and was chosen as the main site for a geochemical survey. Mica schist is widely developed around massive and podiform feldspar veins and large blocky quartz veins.

Figue 2.—Surface geology of Lease 30/1243. Grid coordinates are referred to the north-south baseline.

Most of the talc and chlorite schist has been removed during early excavation to expose the mica schist zone. This is the only location where reaction zoning is clearly defined.

In areas such as this, where the rocks are very heterogeneous, sampling is difficult and results tend to reflect the sampling techniques employed. Some of the problems encountered include: (1) sporadic distribution of beryl, both within the pegmatite and mica schist, (2) interfoliation, on a centimetre scale, of mica and actinolite schist, (3) most rocks, even at depth are extensively altered. Feldspar and hornblende have been hydrothermally altered, probably during the late stages of crystallisation of the pegmatite. Any geochemical trends likely to serve as useful prospecting guides must be established for these altered rocks, since fresh material is rare, (4) small-scale zonal structure in which zone boundaries are gradational and (5) limited outcrop of individual pegmatite veins.

Many of the rocks and minerals were collected only centimetres apart to detect possible compositional changes. Twenty-six samples were collected *in situ* from the open-cut and 10 samples were taken from dumps of material stripped from the schist zone (Table 1).

Ultramafic rock and phlogopite schist

Whole-rock analyses were carried out on 9 samples of ultramafic rock and phlogopite schist (Table 2). Partial analyses for Be, Na, and Cr were carried out on a further 15 samples (Table 3).

Visible beryl crystals were removed from samples before crushing to ascertain whether beryllium is held exclusively in these crystals or is disseminated through the country rock. Results show that up to 312 ppm Be is held either in micro-crystals of beryl or substituted into mica. Beryllium was evidently introduced by the pegmatitic fluids and has permeated the country rock to a maximum distance of 30 cm from pegmatite veins. It is closely associated with feldspar; no trace of beryllium was detected in phlogopite schist enclosing a large, blocky quartz vein. The concentration of beryllium diminishes with distance from the pegmatite; the actinolite zone contains typically low values of about 30 ppm Be. There is, however, no correlation between the concentration of disseminated beryllium and the presence of large beryl crystals.

Schist from the actinolite zone has undergone only moderate alteration by fluids emanating from the pegmatite and hence approximates the composition of the original ultramafic country rock. Its magnesium content of 15-17% MgO indicates a composition intermediate between basaltic komatiite and peridotitic komatiite, but its chromium content is high. Potassium and aluminium, introduced by the invading pegmatite, are enriched in the platy phlogopite and hornblende zones. These zones grade into the ultramafic rock, and the igneous parentage of the phlogopite schist is established by its persistently high chromium content (0.15-0.32% Cr_2O_3). Chromium has evidently not been introduced from elsewhere, and it is concluded that the phlogopite schist was formed by metasomatic alteration of the original ultramafic country rock.

To sum up, the actinolite and phlogopite schist show little compositional variation. Beryl is randomly distributed but limited to within 30 cm of feldspathic pegmatite veins. No geochemical indicators of the presence of beryl in schist are apparent.

Feldspar

Feldspar from 6 pegmatite veins was sampled and analysed. Sample F3 was collected from a large quartz-feldspar porphyry vein near the open-cut (Table 4). The chemical composition of pegmatitic feldspar is quite uniform. Relatively high K_2O, H_2O and MgO contents are attributed to the presence of sericite. Sericitisation probably occurred during the main phase of potassium metasomatism that formed phlogpite reaction zones.

Table 1

List and description of analysed samples

Sample No.	Description of Sample	Analysis†
S5	Phlog. schist along small vein of qtz-feldspar pods.	1
S6	Phlog. schist along small vein 0·7 m above S5.	1
S2	Soft phlog. schist, abundant green blades of clay.	2
S8	Soft phlog. schist, abundant green blades.	1
S3	Phlog. vein sample, strongly interlocked grains.	1
S4	Phlog. schist enclosing blocky qtz vein—no association with feldspar or beryl.	1
S9	Phlog. schist—small green blades, dark green beryl.	1
S10 ⎫	Phlog. schist 0·2 m below S9, more beryl present.	1
B1 ⎬	Medium green beryl crystal from S10, close to felspar.	2
F6	Moderately altered cream feldspar.	2
S12	Phlog. schist bordering F6—coarse green blades, some dark green beryl.	1
F1 ⎫	Yellowish altered feldspar.	2
S13B	Beryl-bearing phlog. schist adjacent to F1	2
S13C ⎬	Beryl-bearing phlog.—abundant green blades.	1
S13D	Contorted schist further from F1, adjacent to S13C.	1
F2 ⎬	Fresh white feldspar from large podiform vein.	2
S14B ⎬	Crenulated phlog. schist enclosing pod of F2	2
B4	Pale emerald green beryl crystal from S14B.	2
S14C ⎦	Soft ultramafic interfoliated with S14B.	1
F4	Fresh feldspar from beryl-bearing vein.	2
F5	Fresh feldspar from beryl-bearing vein.	2
S19C ⎬	Phlog schist—green blades present.	1
S19E ⎦	Phlog. schist adjacent to feldspar vein—contains dark green beryl.	2
UB1	Dark grey-green ultramafic—relict spinifex texture.	1
UB2	Fe-stained ultramafic from trench where beryl occurs.	1
UB3	Schistose ultramafic closely interfoliated with phlog. schist.	1
*DS9 ⎫	Phlog. schist near feldspar vein—green-blades present.	2
*DUB1 ⎰	Schistose ultramafic 2 cm from sample DS9.	2
*DS10 ⎱	Phlog. schist.	2
*DUB2 ⎰	As above.	2
*F7 ⎱	Cream-white feldspar, beryl present.	2
*B3 ⎰	Pale blue-green beryl from F7.	2
*B2	Massive aggregate of dark green, opaque beryl crystals in phlog. schist.	2
*DF16	White feldspar—no association with beryl.	2
*DS2	Phlog. schist containing dark green beryl.	2
*F3	Feldspar (microcline) from qtz-feldspar porphyry near open-cut.	2

Bracketed samples are from the one location.
* Denotes specimens collected from dumps at the treatment plant (i.e. not *in situ*).
†1—AAS analysis for Be, Na, Cr only.   2—Whole-rock analysis.

Table 2

Whole-rock analyses of ultramafic rock (um.) and phlogopite schist samples

Wt. %	DUB 1 (um.)	DS 9	DUB 2 (um.)	DS 10	S 2	S13B	S14B	S19E	DS2
SiO₂	46.83	42.88	44.81	42.99	43.61	42.45	42.34	42.42	43.36
TiO₂	0.38	0.39	0.29	0.37	0.25	0.37	0.37	0.37	0.38
Al₂O₃	9.57	12.57	11.18	12.93	12.16	12.48	12.34	12.39	12.07
Cr₂O₃....	0.18	0.25	0.31	0.24	0.18	0.15	0.18	0.24	0.22
Fe₂O₃....	1.77	2.23	3.41	2.20	3.96	2.81	2.81	2.39	1.88
FeO	8.25	7.53	7.46	7.41	5.14	6.81	7.11	7.20	7.54
MnO	0.23	0.13	0.16	0.12	0.07	0.11	0.14	0.19	0.13
MgO	17.24	17.78	15.65	18.29	17.78	19.54	19.18	19.90	18.69
CaO	6.37	1.88	3.87	1.41	0.14	0.74	0.08	0.01	1.79
Na₂O	0.81	0.55	0.86	0.56	0.56	0.39	0.42	0.44	0.43
K₂O	3.33	5.57	4.14	6.77	6.14	7.19	7.84	7.88	6 84
H₂O⁺....	2.08	3.15	2.61	3.51	3.38	3.16	2.34	2.56	2.18
H₂O⁻....	1.55	2.32	2.39	1.51	3.52	1.61	2.41	2.33	2.30
P₂O₅	0.02	0.06	0.02	0.11	nil	0.09	0.06	0.02	0.01
Be (ppm)	37.0	87.5	31.2	100.0	nil	62.5	12.5	75.0	312.5
Total*	98.61	97.29	97.16	98.42	96.89	97.90	97.62	98.34	97.82

*Consistently low totals are probably due to the presence of small amounts of copper and nickel which were not analysed for.

Microcline is the common feldspar in east-west trending quartz-feldspar porphyry veins near the open-cut. It contains no trace of beryllium or Li₂O. This accords with the view that the porphyry is not related to the beryl mineralisation.

Beryl

The properties of Riverina emerald are as follows (MacKay pers. comm. 1977):

Optical properties

R.I.: 1.573-1.581
Birefringence: 0.008
Optical character: negative
Dichroism: blue-green and yellow-green
U.V. light: inert (due to high ferric oxide content)
Chelsea Filter: brown to pink
Spectroscope: typical for Cr coloured gems; fine absorption lines in red; broad absorption in yellow-green; broad absorption in violet.

Table 3

Be, Na and Cr analyses of ultramafic (um.) and phlogopite schist samples

Sample No.	Be (ppm)	Wt. % Cr₂O₃	Wt. % Na₂O
S3	nil	0.32	0.40
S4	nil	0.25	0.30
S5	nil	0.08	0.41
S6	nil	0.05	0.31
S8	25.0	0.20	0.50
S9	25.0	0.19	0.36
S10	100.0	0.21	0.34
S12	62.5	0·25	0.50
S13C	37.5	0.28	0.83
S13D	25.0	0.24	0.30
S14C	12.5	0.18	0.44
S19C	31.2	0.27	0.51
UB1 (um.)	37.5	0.32	0.73
UB2 (um.)	37.5	0.10	0.31
UB3 (um.)	37.5	0.30	0.52

Table 4

Feldspar analyses. All samples, except F3, contain traces of beryllium

Wt. %	F1 (vein 1)	F2 (vein 2)	F3 Qtz-Feldspar Porphyry	F4 (vein 3)	F5 (vein 3)	F6 (vein 4)	F7 (vein 5)	DF16 (vein 6)
SiO₂	62.26	59.34	65.24	57.98	60.31	57.57	59.54	58.90
TiO₂	nil	nil	nil	nil	nil	nil	nil	nil
Al₂O₃	22.33	25.40	19.21	24.82	24.18	24.61	24.48	25.31
Cr₂O₃	nil	nil	nil	nil	nil	nil	nil	nil
Fe₂O₃	1.27	0.28	0.16	0.84	0.61	0.82	0.31	0.23
FeO	0.09	0.11	0.02	0.17	0.09	0.14	0.08	0.22
MnO	0.01	0.01	nil	0.01	0.01	0.01	0.01	0.01
MgO	0.82	0.41	0.06	0.47	0.80	0.89	0.40	0.75
CaO	0.60	1.16	0.04	1.25	0.91	1.08	0.83	1.11
Na₂O	5.12	7.08	1.95	7.08	6.47	6.94	7.14	8.09
K₂O	3.28	4.01	12.60	3.55	3.27	3.36	3.67	3.35
Li₂O	0.02	0.02	nil	0.02	0.03	0.02	0.02	0.03
Cs₂O	0.14	0.14	0.14	0.16	0.15	0.14	0.17	0.15
H₂O⁺	2.38	1.76	0.09	1.98	2.59	2.53	2.24	1.90
H₂O⁻	1.63	0.61	0.01	1.08	1.12	1.47	1.03	0.39
P₂O₅	0.01	nil	0·02	nil	0·01	0.01	0.01	nil
Total	99.96	100.33	99.54	99.41	100.55	99.59	99.93	100.44

Physical properties

Specific gravity: 2.71-2.75

Inclusions

Healed fractures, many perpendicular to optic axis
Biotite/phlogopite feathers and flakes
Two-phase inclusions (liquid and gas)
Tremolite (?) rods parallel to optic axis.

Analysis

0.23% Cr_2O_3, determined by Atomic Absorption Spectroscopy (Israel).

Geologic association of beryl. Beryl is found in the pegmatite but is often more abundant in the surrounding mica schist. Its colour is a rough index of composition and varies from green and yellow-green to blue-green. Samoilovich *et al.* (1971) propose that the whole range of beryl colourings, from yellow to blue, may be due to the relative concentrations of Fe^{3+} and Fe^{2+} impurity ions in different coordinations. The classification of emerald, without relying on chemical analysis, is rather subjective. In the field only the rich green hue of the emerald variety distinguishes it from common beryl. Unless specifically described as the emerald-green variety, green or dark green beryl referred to in the following sections is assumed to be coloured by iron impurities.

In the pegmatite most of the beryl crystallises as milky blue-green euhedra in albite. Fewer crystals are found in quartz, but they generally have greater transparency. Beryl embedded in feldspar and quartz is normally highly fractured and healed by quartz.

The distinctive coloration of beryl at Riverina distinguishes it from the Poona deposit where only white and colourless beryl are found in the pegmatite (Graindorge 1974). This implies that either iron, which is responsible for the coloration of common beryl, was relatively enriched in the fluids which formed the pegmatite at Riverina, or that these fluids experienced greater interaction with the surrounding ultramafic rock.

Table 5

Beryl analyses

Wt. %			B1	B2	B3	B4
SiO_2	....	....	64.22	64.55	65.06	64.23
TiO_2	....	....	nil	nil	nil	nil
Al_2O_3	....	....	16.53	16.99	16.96	16.47
Cr_2O_3	....	....	0.08	0.04	0.06	0.15
V_2O_3	....	....	0.02	0.02	0.02	0.02
Fe_2O_3	....	....	} 0.93	0.84	0.78	0.94
FeO	....	....				
BeO	....	....	12.72	12.95	12.99	13.07
MnO	....	....	nil	nil	nil	nil
MgO	....	....	1.29	0.89	0.86	1.04
CaO	....	....	nil	nil	0.03	nil
Na_2O	....	....	1.13	1.28	0.60	1.44
K_2O	....	....	0.11	0.04	0.08	0.07
Li_2O	....	....	0.04	0.04	0.04	0.05
Cs_2O	....	....	0.10	0.13	0.02	0.14
H_2O^+	....	....	2.40	1.96	1.95	2.01
H_2O^-	....	....	0.03	0.01	0 07	0.02
P_2O_5	....	....	0 01	nil	nil	nil
Total	....	....	99.61	99.74	99.52	99.65

Sample colours, according to the Pantone Matching System, are B1—green (Pantone 346), B2—yellow-green (Pantone 351), B3—blue-green (Pantone 338), B4—emerald green (Pantone 334).

Chemical analysis of blue-green beryl (specimen B3) separated from feldspar reveals the presence of 0.06% Cr_2O_3, 0.02% V_2O_3 and 0.86% MgO (Table 5). These elements are normally removed from a magma during early crystallisation and separation of chromite and ferromagnesium minerals. Their presence in the pegmatite phase suggests they have been incorporated from the ultramafic country rock during crystallisation of the pegmatite.

Beryl in the mica schist is restricted to the hornblende and platy phlogopite zones and displays a wide range of colour and crystal form. Common green and yellow-green beryl is most abundant. Rarer emerald is almost exclusively found in platy phlogopite schist, although several pale crystals have been found intergrown with quartz and feldspar at the vein-schist contact. Three crystals of goshenite (colourless beryl) have also been found.

Hexagonal prisms up to 2 cm in length are common and are usually aligned along schistosity planes. In many places porphyroblastic textures are present, indicating growth of the crystals in a solid state. Radial and bent crystals are found rarely. Goshenite has a tabular habit and prism faces are striated parallel to the c-axis. Emerald occurs generally as single, prismatic crystals embedded in the folio of phlogopite schist.

No pattern is evident in the distribution of coloured beryl. This poses the problem of why some beryl crystals contain chromium impurities, whereas others contain mainly iron. One solution would be the partitioning of elements such as chromium, iron, and vanadium between the beryl and schist adjacent to it. Emerald would be expected to crystallise in phlogopite schist with high chromium content; common green and colourless beryl in schist with low chromium content. However, it is common to find beryl crystals, ranging from yellow-green to dark green, closely associated in a small area of phlogopite schist. Less commonly, emerald crystals are found only several millimetres from drab yellow-green beryl. Such small-scale compositional changes in the schist are unlikely; hence partitioning of elements between beryl and the adjacent schist cannot be responsible for the colour difference. Rather, it seems that a time factor is involved. Incorporation of elements, such as chromium, into beryllium-bearing solutions apparently depends on the length of time that they remain in contact with the ultramafic host rock. This is discussed further in the following sections.

Chemical analysis. Beryl from the pegmatite and mica schist was sampled and analysed. Blue-green beryl (B3) was separated from feldspar. Other beryl samples extracted from phlogopite schist vary from dark green (B1 and B2) to pale emerald green (B4). In general, beryl crystals become progressively darker in colour with increasing distance from the pegmatite.

Chromium in the range 0.14-0.50% Cr_2O_3 produces the unique emerald colour. Sample B4 contains sufficient chromium to be classified as emerald, as defined by Anderson (1966), but the other beryl samples contain only 0.04-0.08% Cr_2O_3. No trace of chromium was detected in feldspar from which sample B3 was separated, yet this beryl contains

0.06% Cr_2O_3. This presumably came from the only source of chromium in the area—ultramafic and phlogopite schist. Vanadium is also present, but in amounts too small to influence coloration.

Beryl from the schist has a uniform chemical composition. Pegmatitic beryl differs in that it has low Na_2O and Cs_2O and is the only beryl that contains calcium.

Sodium in the pegmatite is held almost exclusively in albite. The associated beryl contains only 0.60% Na_2O. The concentration of sodium dispersed through the phlogopite schist increases with distance from the pegmatite. Beryl in schist also reflects this trend and its sodium content increases to a maximum of 1.28% Na_2O, indicating progressive alkali enrichment of the fluids which diffused into the country rock. This has important implications for the genesis of beryl.

In normal pegmatites the multigeneration sequences of beryl, crystallising inwards from the vein margins to the cores and metasomatic units, are known to increase in alkali content (Heinrich 1953). There is no simple analogy between the crystallisation trends of crossing-line pegmatites and these more common types found in granitic terrains. The latter are usually zoned and crystallise from the margin to the core. Crossing-line pegmatites, however, occur as narrow unzoned veins. Alkali enrichment of beryl crystals in mica schist at Riverina suggests that they represent the final stage of beryl crystallisation. It is argued therefore that beryl in the schist formed subsequent to crystallisation of the pegmatite veins. Reaction with the ultramafic would be promoted by prolonged circulation of beryllium-bearing fluids and would account for the dark green coloration of beryl in phlogopite schist.

Thin-section study. Beryl in sericitised feldspar forms euhedral crystals, weakly zoned with few inclusions. No alteration is apparent. Crystal forms of beryl in mica schist are more varied. Small clusters and single crystals form well-developed, hexagonal prisms, but beryl also grows profusely as anhedral aggregates partly intergrown with phlogopite. Most of the individual beryl crystals are zoned. Zoning in hexagonal cross-sections is distinguished by marked variations in refractive index. Cêrny and Turnock (1975) have shown that R.I. becomes higher with increasing alkali content. In keeping with the overall alkali enrichment during pegmatite crystallisation, the outer parts of the crystals almost invariably show R.I. and alkali contents higher than those of the cores.

Beryl and hornblende coexist in the hornblende zone. No reaction is observed at grain contacts, indicating chemical equilibrium between the minerals. They have crystallised almost simultaneously, and where the beryl and hornblende compete for the same space, neither asserts a regular crystal form.

Since most of the minerals of rocks associated with the pegmatite were formed almost simultaneously, these externally paragenetic minerals are encountered again as inclusions in beryl. Phlogopite is by far the most frequent mineral inclusion, often extending from the phlogopite schist into the beryl, partly irregularly and partly along cracks parallel to the basal plane. Also, phlogopite laminae are strewn singly throughout the crystal or filed into parallel or irregular rows. Phlogopite is not everywhere well-preserved and some is iron-stained or partially resorbed.

Most beryl crystals are studded with dusty opaque grains that are normally dispersed throughout the entire crystal but are also concentrated in bands roughly parallel to the basal plane. Actinolite rods, aligned parallel to the c-axis, are less common; tubes parallel to the c-axis are found rarely.

Syngenetic inclusions, formed during beryl crystallisation, are mainly two-phase inclusions (liquid with gas bubble); no three-phase inclusions are present. The only post-crystallisation inclusion is secondary quartz which heals fractures.

Electron microprobe analysis. Basal sections of two beryl crystals were analysed by electron microprobe to determine whether there is zoning with respect to chromium and to ascertain if there is a correlation between chromium content and colour of beryl. Chromium K values were measured at an average of ten points in each crystal. A theoretical calibration factor to convert K values to weight per cent Cr_2O_3 was calculated by counting the chromite standard and assuming that the beryl had the ideal composition $Be_3Al_2Si_6O_{18}$.
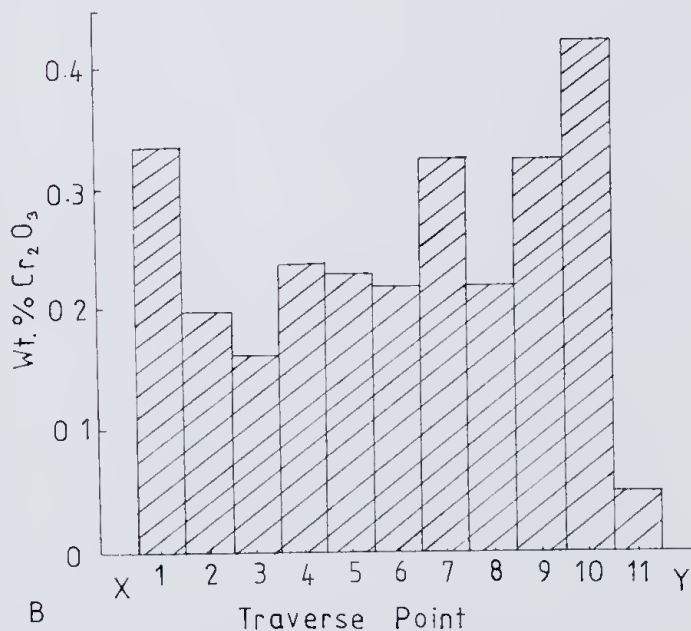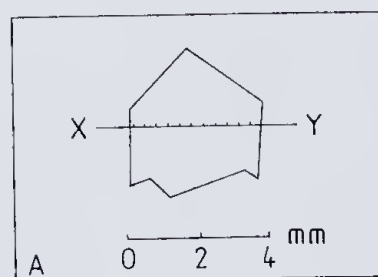

Figure 3.—A. Map of electron microprobe traverse X-Y across the basal section of a blue-green beryl crystal. A complete chemical analysis of this beryl (sample B3) is given in Table 5. B. Variation in weight per cent of Cr_2O_3 along traverse X-Y.

The chromium content of a single blue-green beryl crystal from feldspar (sample B3) varies from 0.05-0.42% Cr_2O_3 (Fig. 3). The variation is irregular, but the outer part of the crystal generally has the highest chromium concentration. A narrow rim of colourless beryl contains only 0.05% Cr_2O_3 (traverse point 11)—insufficient to produce green coloration. This inhomogeneity of composition, even within a single crystal, indicates that bulk chemical analysis only yields an average composition. A complete chemical analysis of another beryl crystal from sample B3 is given in Table 5. Even when taking averaging into account, it contains almost 0.2% less Cr_2O_3 than the crystal analysed by electron microprobe. Hence, chromium content varies not only within single crystals, but also significantly among crystals found only centimetres apart in the same mineralogical environment.

Emerald also has variable chromium content. A correlation between colour and chromium content is clearly established from the results of the analysis of a dark green crystal with colourless core (Fig. 4). The green areas contain a persistently high chromium content of 0.32-0.43% Cr_2O_3, whereas the colourless core contains only 0.03-0.06% Cr_2O_2. Enrichment of chromium in the late growth stages of single crystals of green beryl is characteristic of the Riverina deposit and is an important indicator of their genesis.

Beryl, like many minerals, displays growth anisotropy and grows preferentially in the direction of the c-axis. Its crystals are dominantly bounded by the slowest-growing faces. Colour zoning (and hence partitioning of chromium) is common and may run parallel to prism faces or to the basal plane. Short-term variations in the amount of chromium incorporated into the crystal lattice are recorded by colour changes along the length of the prism. However, zoning in the slowest growing part of the crystal, parallel to the basal plane, implies that fluctuations in the amount of chromium available have been operative over a relatively long time interval.

Gübelin (1956) records the presence of colourless beryl with green cores at Habachtal, Austria, and has assumed therefore that Cr_2O_3 was exhausted during the early phase of beryl crystallisation which resulted in emerald. An earlier phase of colourless beryl crystallisation is, however, evident at Riverina. Within single crystals the Cr_2O_3 content progressively increases outwards from the core. Discrete crystals of high alkali colourless or pale beryl (e.g. goshenite) form last.

In summary, beryl crystallises early as colourless or pale crystals and later as green crystals (including emerald) as chromium is released from the country rock and is incorporated into the mineral lattice. Beryl continues to crystallise when chromium is depleted or exhausted.

Discussion

Literature review

Emerald occurs in two distinct geological environments: (1) biotite and ultramafic schist zones associated with pegmatites and (2) low-temperature veins in sediments. Although schist deposits have been regarded as the "classical" occurrence, most of the world's finest emeralds have come from Columbia, where they are found in veins in sediments. A comprehensive report on the localities and characteristics of the world's known emerald deposits is given by Webster (1975).

Schist deposits. All occurrences of this type include ultramafic rocks or their metamorphic derivatives, which show evidence of pegmatitic activity (Hickman 1972). Situated in igneous-metamorphic terrains, emerald usually occurs in different assemblages of serpentine-biotite-chlorite-tremolite-talc rocks. Emerald has been found in these schistose host rocks in India, Transvaal, Brazil, Urals, Rhodesia, Zambia, the Habachtal (Austria) and a few other less-important localities.

Tourmaline, apatite and minor fluorite often accompany emerald mineralisation. Bank (1974), Muktinah and Banerjee (1969), and others cite the co-existence of these minerals with emerald as
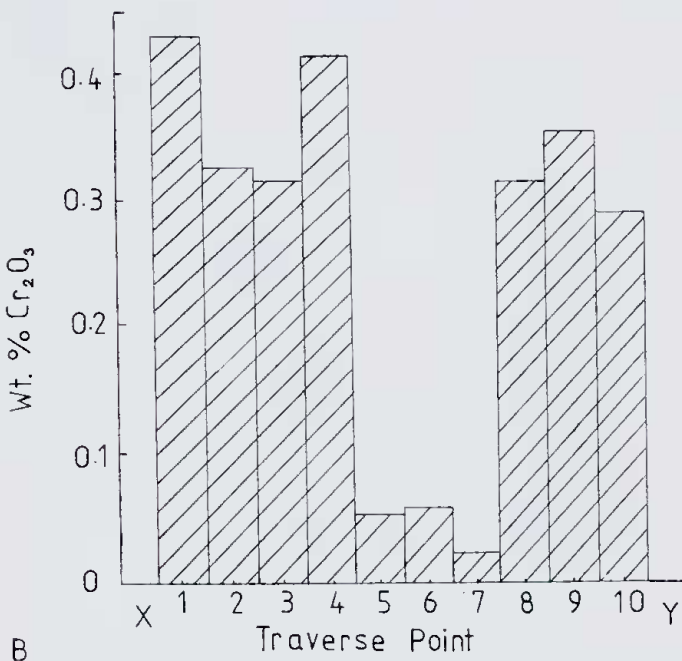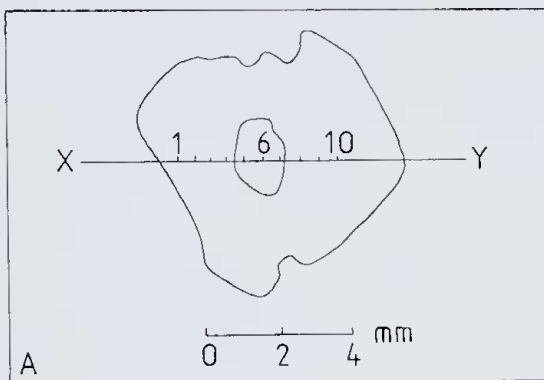

Figure 4.—A. Map of electron microprobe traverse X-Y across the basal section of an emerald-green beryl crystal. Traverse points 1-4 and 8-10 are in the dark green areas and points 5-7 are within the colourless core. B. Variation in weight per cent of Cr_2O_3 along traverse X-Y.

evidence for the migration of volatile-rich pegmatitic fluids into the adjacent country rocks. The colour produced by chromium distinguishes emerald from common beryl and, consequently, interest has been focused on the source of this element. The dependence of the intensity of the green colour upon the quantity of chromium present has been established by Herman and Wussow (1935). Many authors have been content to assume that this chromium is derived from the ultramafic rocks associated with the emerald deposits. Datta (1966), in the study of the Rajgarh Area of India, appears to be the only author who has verified that the ultramafic recrystallised mica schist have a persistently high chromium content (0.11% Cr), compared with low values (0.02% Cr) for the pegmatite.

In summary, it is widely accepted that emerald results, at least in part, from the presence of chrome-bearing rocks of ultramafic association during pegmatite intrusion. This model has been applied to the West Australian emerald deposits at Poona and Menzies by Graindorge (1974) and Whitfield (1975) respectively.

Vein deposits. The major sources of Columbian emerald are the Chivor, Muzo, and Cosquez mines. Johnson (1961) reports that at Chivor emerald is commonly found in 'strings' and 'pockets' in fissure cracks through thick beds of shale. Albite and pyrite are the principal gangue minerals. The geology of the Muzo-Cosquez area is fundamentally similar to Chivor. Here, the emerald-bearing veins, containing calcite, quartz, dolomite and pyrite, run through country rocks of black carbonaceous limestone and shale.

These deposits are unique and the source of emerald mineralisation remains a point of contention. The assumption of hidden igneous rocks at depth seems unsatisfactory as deep erosion has failed to expose them. Feininger (1970) supports an earlier theory that envisages low-temperature formation of emerald by lateral secretion from circulating mineralising waters.

Riverina deposit

Unlike most emerald deposits of this type, the mineralogy of the Riverina deposit is relatively simple. The beryl deposit is not complicated by the presence of other minerals (such as tourmaline, apatite and fluorite) and provides an ideal model to study the paragenesis of beryl. Emerald cannot be studied in isolation because it forms only a small part of the multi-generation sequence of beryl.

Beryllium has been introduced in association with a series of narrow, irregularly shaped pegmatite veins which intrude a large ultramafic body. Phlogopite schist borders the pegmatite veins and grades into actinolite-chlorite-talc schist which comprises the ultramafic country rock. The igneous parentage of this group of schistose rocks is established on the basis of field relations, and their high chromium content (0.15-0.32% Cr_2O_3). Beryl is the only beryllium-bearing mineral formed and is found embedded in the quartz-albite pegmatite and disseminated in the phlogopite schist.

The mineral assemblages of altered rocks in the vicinity of the pegmatite have been formed by metasomatic processes. The country rock consists of actinolite/tremolite, chlorite, talc and chromium. The formation of phlogopite, hornblende and beryl required the introduction of potassium and beryllium. The well-developed fissility and schistosity of these rocks has favoured rich concentrations of volatiles, and phlogopite schist is apparently developed as a result of potassium metasomatism consequent on the emplacement of the pegmatite.

The multigeneration beryl sequence has a complex crystallisation history. Beryllium-bearing fluids have permeated the country rocks to a maximum distance of 30 cm from the pegmatite. Dark green beryl from phlogopite schist has higher alkali content than blue-green beryl from the pegmatite. Fluids are known to increase progressively in alkali content during the pegmatitic crystallisation process, which implies that beryl in the schist formed after crystallisation of the pegmatite veins. Prolonged circulation of beryllium-bearing solutions has apparently promoted reaction with the chrome-bearing ultramafic country rock.

Chromium is present in dark green beryl from the schist, but the results of chemical analysis of a sample of pegmatitic beryl show that it also contains chromium, though in much lower concentration; 0.06% Cr_2O_3 as compared to 0.15% Cr_2O_3 in pale emerald green beryl. Feldspar intergrown with this beryl contains no trace of chromium. It is apparent that beryllium-bearing solutions extract chromium from the ultramafic rocks and crystallise as emerald and dark green beryl. Chromium is not taken up by the other pegmatitic fluids that form the quartz-feldspar pegmatite.

Chromium content varies among crystals and within single, zoned crystals. Colourless and pale green beryl form first, followed by crystallisation of dark green beryl, coloured by chromium, in phlogopite schist. High alkali, chromium-deficient crystals form in the final stage of beryl crystallisation. This shows that chromium is incorporated into beryl during the intermediate stage, some time after intrusion of the pegmatite. The specific source of chromium in the ultramafic country rock has not been determined. Chromite is an extremely refractory mineral and hence an unlikely source. It seems that small amounts of chromium, substituted into mica and other silicates, were released from the ultramafic country rock during its alteration to phlogopite schist.

In summary, the results of this study support the traditional model of formation of emerald. Beryllium and potassium rich solutions from pegmatite veins have penetrated along structurally weak planes in the enclosing ultramafic schist. Potassium reacts with Mg-silicates in the ultramafic rock and forms phlogopite schist; beryllium-bearing solutions extract chromium and crystallise as emerald. Hydrothermal alteration of feldspar and hornblende is effected by the circulation of chemically active fluids during the late stage of crystallisation of the pegmatite. Emerald owes its formation to the complex interaction of pegmatitic, hydrothermal and pneumatolytic processes.

References

Anderson, B. W. (1966).—Chromium as a criterion for emerald. *J. Gemmology,* **10**: 41-45.

Bank, H. (1974).—The emerald occurrence of Miku, Zambia. *J. Gemmology,* **14**: 8-15.

Beus, A. A. (1962).—*Beryllium.* Freeman and Company, San Francisco and London.

Cêrny, P. and Turnock, A. C. (1975).—Beryl from the granitic pegmatites at Greer Lake, Southeastern Manitoba. *Can. Mineralogist,* **13**: 55-61.

Datta, A. K. (1966).—Geological milieu of emeralds in the Rajgarh area, Ajmer district, Rajasthan. *Bull. Geol. Soc. India,* **3**: 29-33.

Deer, W. A., Howie, R. A. and Zussman, J. (1966).—*An introduction to the Rock Forming Minerals.* Longmans, London.

Feininger, T. (1970).—Emerald mining in Columbia: history and geology. *Min. Record,* **1**: 142-149.

Glover, J. E. (1968).—Western Australian emeralds. *Aust. Gemm.,* **10**: 15-17.

Graindorge, J. M. (1974).—A gemmological study of emerald from Poona, Western Australia. *Anst. Gemm.,* **12**: 75-80

Gübelin, E. J. (1956).—The emerald from Habachtal. *Gems and Gemmology,* **8**: 295-309.

Heinrich, E. W. (1953).—Chemical differentiation of multigeneration pegmatite minerals. *Am. Miner.,* **38**: 43.

Herman, F. and Wussow, D. (1935).—The emerald deposits of the world. *Mining Mag.,* **53**: 20-25.

Hickman, A. C. J. (1972)—The Miku emerald deposit. *Ec. Report No. 27, Rep. of Zambia, Geol. Snrv. Dept.*

Johnson, P. W. (1961).—The Chivor emerald mine. *J. Gemmology,* **8**: 126-152.

Kriewaldt, M. (1970)—Menzies, Western Australia, Sheet SH/5i-5. Geol. Surv. W.A. *1:250 000 Geol. Series Explanatory Notes.*

Muktinah, N. C. and Banerjee, S. N. (1969).—Emerald mineralisation in Rajgarh-Chat-Bithur area, Ajmer district, Rajasthan. *Indian Sci. Congr. Ass., 56th Sess, Proc, Part 3:* 237.

Samoilovich, M. I., Tsinober, L. I. and Duninbarkovski, R. L. (1971) Nature of the colouring in iron-containing beryl. *Sov. Phys.—Crystallography,* **16**: 147-150.

Taylor, A. M. (1967)—Synthetic vanadium emerald *J. Gemmology,* **10**: 211-217.

Webster, R. (1975).—*Gems.* Newnes-Butterworths, London.

Whitfield, G B. (1975). Emerald occurrence near Menzies, Western Australia *Aust. Gemm.,* **12**: 150-152.